# Less is more – Design principles for joint-less bridges

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## ABSTRACT

Unrestrained economic growth raises the question of how mankind will deal with its resources in the future. Resources mean not only materials, energy and environment but also aesthetics and culture heritage.

Bridges are important elements of the public infrastructure system. Their dimensions and scale require a responsible and creative approach at the conceptual design – the so-called “birth stage of a bridge”.

In the following article, three important design criteria will be discussed: resource consumption, structural robustness and the contribution to the culture heritage.

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## NATURE AS TEACHER

Straight lines, planar surfaces and rectangular angels are unknown by nature. Biological structures, as a result of long evolution, develop based on criteria that differ from those used by civil engineers when designing structures. Trees and bones are always strengthened at areas exposed to large forces by the process called “adaptive growth” so that stress concentrations are avoided. The nature avoids redundancy (waste of material) and overloading. The result is a very strong and optimized natural structure. Compared to many technical structures natural structures are characterised by means of a continuous form based on an efficient flow of forces. (see Figure 1).

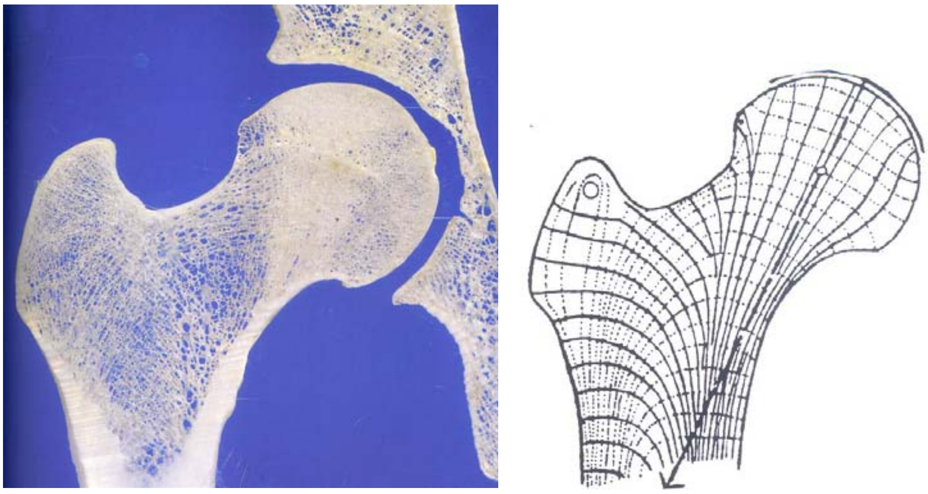

Figure 1. Distribution of principle stresses inside a bone joint
(Nachtigall et al., 2000)

## WEIGHT AS A CHALLENGE

The efficiency of bridge structures, however, highly depends upon the permanent loads, as these utilize a large part of the load-bearing capacity. Only a relative small part of the structural load bearing capacity is available for carrying traffic loads. In the case of conventional road bridges made of concrete, permanent loads have comprise up to 70% of the total load. In the case of filigree pedestrian bridges made of concrete and/or steel, permanent and non-permanent loads comprise a nearly equal share on the total loads carried by the bridge.

Due to the worldwide declining availability of resources and the ever-increasing impact on the environment caused by pollutants and waste, the optimized use of resources and energy in the construction industry is becoming increasingly important. After all, the construction industry consumes about 35% of energy, causes about 35% of emissions, and uses about 50% of resources (Jischa, 2007). Therefore, the environmental and social impact of technical solutions must have priority in the future. In the automotive and aircraft industry, the material consumption has been continuously reduced by the introduction of new structural concepts (e.g. integral design) and by adoption of new materials, such as carbon fibre composites.

As a parameter for the comprehensive efficiency of structures the following characteristic values are available:

a. Breaking length L:

$$L = f/\gamma \tag{1}$$

f – strength [N/mm$^2$]
$\gamma$ – density [kN/m$^3$]

Examples:
concrete (C 20/25 to C 50/60): $L_c$ = 1,0km
steel (S 235 to S 460): $L_s$ = 4,5 km

b. Value of lightweight (in german: „LBK“):

$$LBK = F_{total}/F_g \tag{2}$$

$F_{total}$ – internal force due to total load [kN]
$F_g$ – internal force due to dead load [kN]

c. Efficiency of embodied energy E:

$$E = e/f \tag{3}$$

e – embodied energy [MJ/kg]
f – strength [N/mm$^2$]

Examples:
concrete (C 20/25 to C 50/60):$E_c$ = 3,5 x $10^{-2}$ MJ mm$^2$/N kg
steel (S 235 to S 460):$E_s$ = 7,5 x $10^{-2}$ MJ mm$^2$/N kg

Above examples clearly show that steel is better than concrete concerning load-bearing efficiency, while neglecting the embodied energy. Taking into account embodied energy concrete structures promotes more sustainable solutions.

Efficient materials, computer-based manufacturing facilities, and the development of new structural systems can lead to a relative reduction in the use of resources. The 1,177 m long Ting Kau Bridge in Hong Kong is a prominent example for such a new structural concept. Three slender towers like the masts of a sailing boat are braced by cables in the longitudinal and transverse directions of the bridge. Therefore the slenderness of the towers appear well- proportioned. Furthermore, the braced structure gains robustness against the significant potential typhoon and earthquake loads (see Figure 2).

Figure 2. Ting Kau Bridge in Hong Kong, China

Modern stadia roofs are characterized by a minimized self weight. For example, Jörg Schlaich invented a completely new structural system for covering big stadia realized for the first time in Stuttgart in 1993. The principle of the design came from the spokes wheel of a bicycle (in german: „Speichenrad“). Notably, prestressed high strength cables have the capacity to bridge large spans with a minimum amount of material they are very exp. However, they are very expensive, if they are back-anchored. To overcome this, looped cable roofs combine the favorable characteristics of cable and membrane structures. Many such looped cable roofs have been built worldwide. One of the biggest is the World Cup stadium in Cape Town which has the capacity of 64.000 spectators (see Figure 3).

Figure 3. Cape Town Stadium in Kapstadt, South Africa

## PPORTUNITIES IN MONOLITHIC CONCRETE

Eduardo Torroja, the genius spanish engineer and instructor writes about concrete in his book “Die Logik der Form” (Torroja, 1961): "To the classical builder, concrete is thus a moldable material which has yet to turn to stone. However this is not happening within mutually independent splices held together by ashlars, but within enormous monoliths." In terms of concrete bridge construction, unfortunately Torroja’s expectation has only been fulfilled. Although predestinated for a marginally monolithic system, special building techniques like incremental launching and the precast method, concerns about uncontrolled cracking as a result of constraint stresses have hindered the development of jointless constructions. Only sporadically and together with very innovative owners has been possible to build some trendsetting bridges in Germany using some of these concepts (see Figure 4).

Figure 4. Auerbach-Bridge, Stuttgart (Schlaich et al., 2004)

The advantages of jointless construction methods are well known, as explained by Pötzl, 1996, Burke, 2009, Glitsch, 2013. Bridge builders know that quality and sustainably can be improved by omitting bearings and joints ("the best bearing is no bearing"). In summary, the use of monolithic concrete offers the following advantages:

- Lower manufacturing and maintenance costs
- No annoying sound sources
- No jolting of vehicles
- Higher redundancy and respectively, a lower probability of failure
- More creative freedom in the conceptual design

## THE CONCENTUAL DESIGN STAGE AS THE "BIRTH OF THE BRIDGE"

The extraordinary goal in designing jointless bridges is to minimize the constraint stresses due to shrinkage and changes of temperature. Very often the engineers concentrate to the best computer model for calculation or think about the solution of structural details (eg exact arrangement of the approach slab). Occasionally concrete technological measures (e.g. cooling of the concrete) or special manufacturing processes are undertaken (e.g. shrinkage gaps in the superstructure under construction).

Unfortunately, the exceptional potential during the conceptual design stage often remains unexplored. Especially during this early stage the greatest freedom exists to „navigate" the constraint stresses, because structural flexibility can be consequently used. Figure 5 shows the first classification ("system") of jointless bridges in regard to the geometry in plan and the support conditions at the ends of the bridge. Both play critical functions during the "birth" of a bridge.

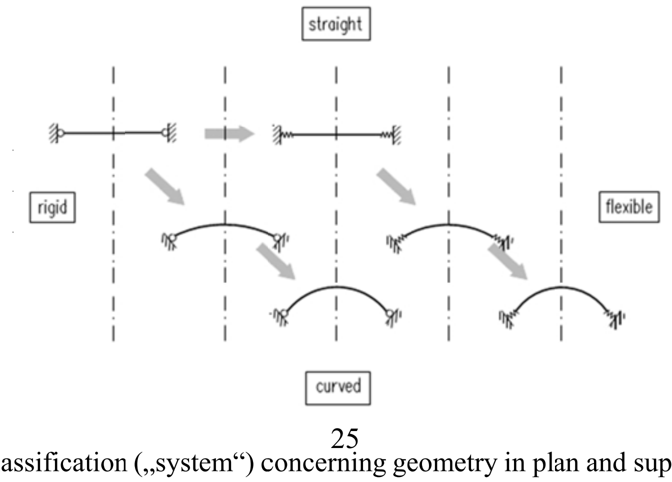

Figure 5. Classification („system") concerning geometry in plan and support condition

Due to this classification, three main phenomena can be considered:

a) Case 1: straight and rigid

In straight bridges with rigid abutments the constraint stresses will exclusively be reduced by cracks in the superstructure. The technological effort for rigid abutments is only suitable for long bridges, since constraint stresses are independent of the bridge length! For short and intermediate bridges, this approach is far too expensive. The resulting constraint force N depends on the axial stiffness and in general it is very high.

$$N = \varepsilon \, EA \text{ [kN]} \tag{4}$$

EA – axial stiffness [kN]
$\varepsilon$ – strain due to shrinkage and temperature [-]

b) Case 2: straight and flexible

By using flexible abutment walls and dispensing the high rigidity of the abutments, the longitudinal changes of the superstructure can be absorbed with less constraint stresses (Pötzl et al., 2005). The premise is that no damage occurs at the backfill nor at the road surface e.g. by settlements due to a backfill slide when temperature decreases in winter or due to an uplift when earth pressure increases at the surface due to higher temperatures in summer (see Figure 6).

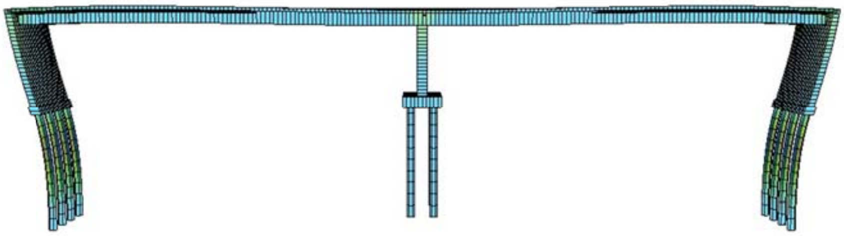

Figure 6. Deformations of flexible abutments in summe

Both phenomena can be avoided by a “modified” backfill. The summer-phenomenon is eliminated through the use of a compressive layer of polystyrene placed between the abutment wall and the backfill, so that the longitudinal changes of the superstructure are absorbed in this layer. For the winter-phenomenon, horizontal layers of geogrid can provide structural stability of the backfill without supporting the abutment (see Figure 7).

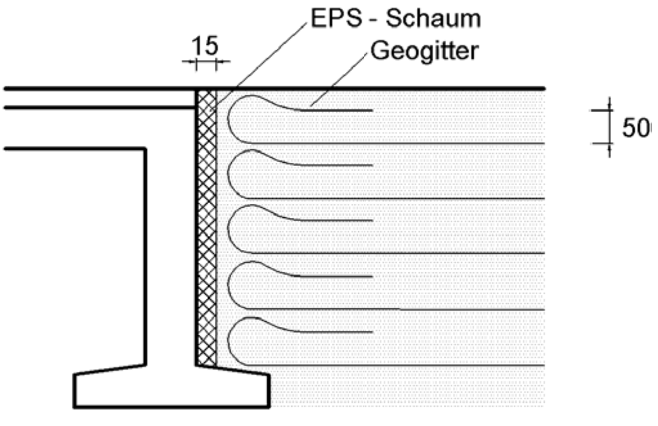

Figure 7. Layout of the flexible backfill construction

In order to measure deformations and their influence on the backfill, a large-scale test was executed in the testing facilities at Landesgewerbeanstalt Bayern, a public-law corporation based in Nuremberg. A modified backfill was installed in a 8,0 m long, 3,0 m wide and 5,0 m deep testing pit. With these dimensions, it was possible to simulate one part of an abutment subdivided in longitudinal bridge direction. Physical testing results were confirmed with numerical modelling applying non-linear calculations with the FE-system PLAXIS at Coburg University.

Earth pressure on the abutment wall arises exclusively when soil deformations occur towards the backfill, which happens in summer. In the winter, the modified backfill keeps its stability. No significant tensile forces were measured inside the geogrid. Vertical deformations of the surface were first detected at wall head movements of about 120 mm. In that case, a fast disapating uplift of 10 mm occurred 2,0 m behind the abutment wall. The test showed that the surface deformations, even under excessive wall movements, can significantly reduced by using an optimal installed backfill and a sufficiently dimensioned layer of polystyrene.

Because of this, no dangerous deformations at the surface of the backfill were predicted under

expected serviceability loads.

This special “Coburg abutment” has been installed a number of times. The largest project so far is the Taxiway Bridge East 1 at Frankfurt Airport constructed in 2012 (see Figure 8 and 9). The three span T-shaped bridge with a 92 m length was designed for a total load of 750 tons to accommodate current aircraft models. The overall deck area is nearly 20.000 m$^2$. Hence,

this bridge is one of the largest integral bridges in Europe (Steiger et al., 2012).

Figure 8. Taxiway-Bridge East 1 at Frankfurt Airport, Germany

Figure 9. Backfill under construction

c) Case 3: curved and rigid

The advantage of curved bridges is that the superstructure can “escape” transversally. Therefore, the constraint stresses decrease depending on the increasing angle α and the decreasing stiffness of the superstructure and the piers. The constraint stresses are a fraction of those of a straight bridge (see Figure 10).

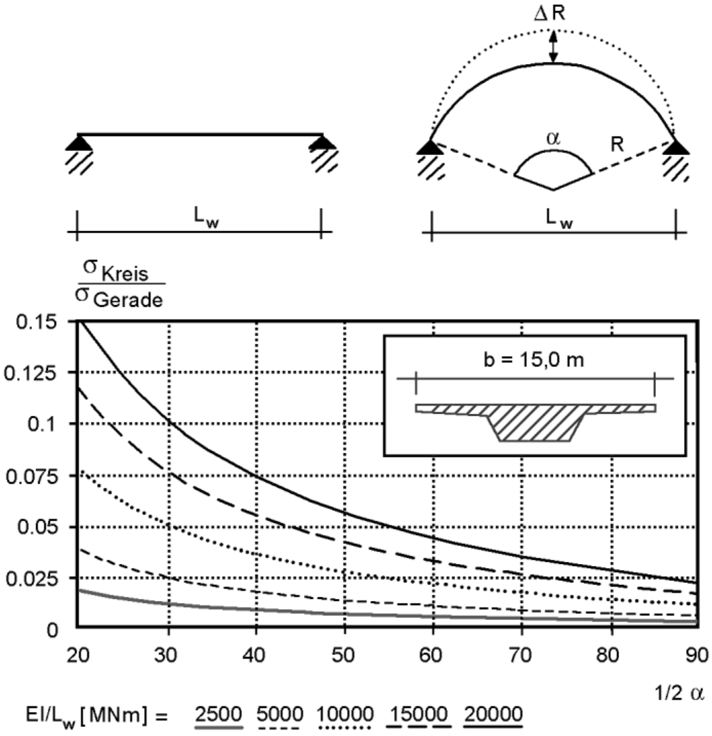

Figure 10. Comparison of maximum constraint stresses#
(Pötzl et al., 2005)

One of the most famous and curved bridges is the 526 m long Sunniberg-Bridge in Switzerland designed by Christian Menn (see Figure 11).

Figure 11. Sunniberg-Bridge near Klosters, Switzerland

The second classification („topography ") concerns the situation of the gradient over ground. With increasing height H of the bridge, the span l naturally becomes larger. This leads, however, to a disproportional increase of the height h and EA (see equation (4)), as well as the constraint stresses (see Figure 12). A goal of conceptual design must be to use the topographic conditions consistently for the reduction of the constraint stresses.

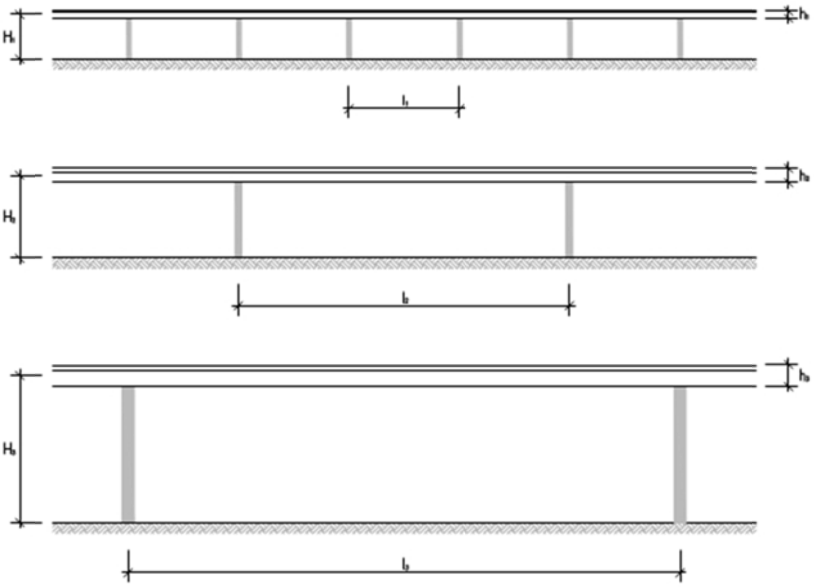

Figure 12. Classification („topography“) concerning gradient of the bridge

In general for bridges of more than 200 m in length, the integral construction method is not accepted, although it is well known that the constraint stresses are independent of the bridge length (see equation (4)). The idea that the longitudinal strain due to shrinkage and temperature can occur only by moderate cracking is not accepted. An exception is the Nesenbachtal-bridge in Stuttgart (Germany) completed in 1999 (Schlaich et al., 2000). Tunnels at both bridge ends are rigid, and serve as cheap abutments (see Figure 13). The concrete deck slab with a small thickness of 25 cm and the very slender steel truss reduce the constraint stresses. Extensive measurements have shown that the crack widths are not larger than 0.30 mm (Pötzl et al., 2001). After 15 years, the durability of the whole concrete structure has been proven.

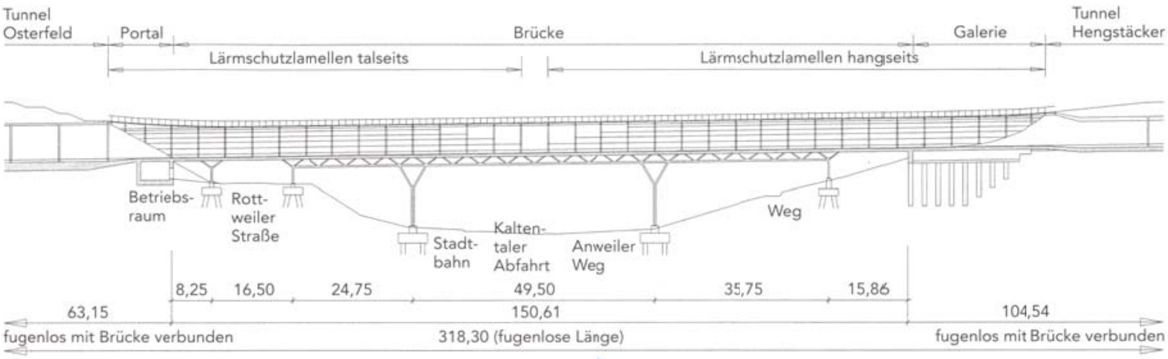

Figure 13. Nesenbachtal-Bridge (with both tunnels) in Stuttgart, Germany

As an alternative, semi-integral bridges have been built all over the world. In Germany semi- integral bridge involves at least two piles that are monolithically connected to the superstructure (Glitsch, 2013). In the case of multi-span bridges (in general more than four spans), this means that many jointless sections are divided by expansion joints. The superstructure can be fixed or longitudinally moveable connected to the abutments.

For the ICE-high-speed railway line Erfurt-Leipzig, four semi-integral bridges were completed in 2013. The biggest one was the 1,001 m long Gänsebach valley bridge. Its construction marks the first time that such a large bridge was designed according to the new Deutsche Bahn AG guideline (Deutsche Bahn, 2008). As is typical for such designs robustness was critical to generate low, long-term maintenance costs, as well as a harmonious integration into the shallow valley. In order to carry the significant breaking loads and at the same time achieving a slender column design two different solutions were in the following two projects.

In the case of the 573 m long multi-span Scherkonde valley bridge, the western abutment was fixed, resulting in a necessary expansion joint only at the eastern abutment (see Figure 14). The extremely long jointless portion was possible through the use of slender concrete columns with a reduced modulus of elasticity and a special erection method. Reducing the constraint stresses due to shrinkage, the fixed point was changed during construction from the east abutment to west one (Marx et a., 2010).

Figure 14. Scherkonde valley bridge near Weimar, Germany

In the case of the 1,001 m long Gänsebach valley bridge (Schenkel et al., 2010) and the 297 m long Stöbnitz valley bridge (Jung et al., 2011), the superstructures were divided into several jointless sections. In order to transmit the breaking loads special V-shaped frames were provided in the middle of each section (see Figure 15).

Figure 15. Gänsebach valley bridge near Weimar, Germany
View and V-shaped frames under construction

Figure 16. Stöbnitz valley bridge (visualization) near Merseburg, Germany

## CONCLUSION

Joint-less bridges give three convincing answers to future requirements in bridge design:

1. With regard to the embodied energy of concrete in combination with the loadbearing efficiency concrete is an old and very young respectively sustainable material.
2. Joint-less bridges are durable structures without any sensitive components combined with small maintenance costs and a high level of redundancy.
3. With regard to the aesthetics joint-less bridges offer greater creative freedom at the conceptual design stage and give the opportunity to demonstrate that each bridge much to be considered important, as it transforms the landscape.

This means the concept „Less is more“. It should be the motto for the future. Klaus Stiglat, a civil engineer and cartoonist gives his own but not serious answer: „Due to the low budget, we will install the cables five years later“ (see Figure 17).

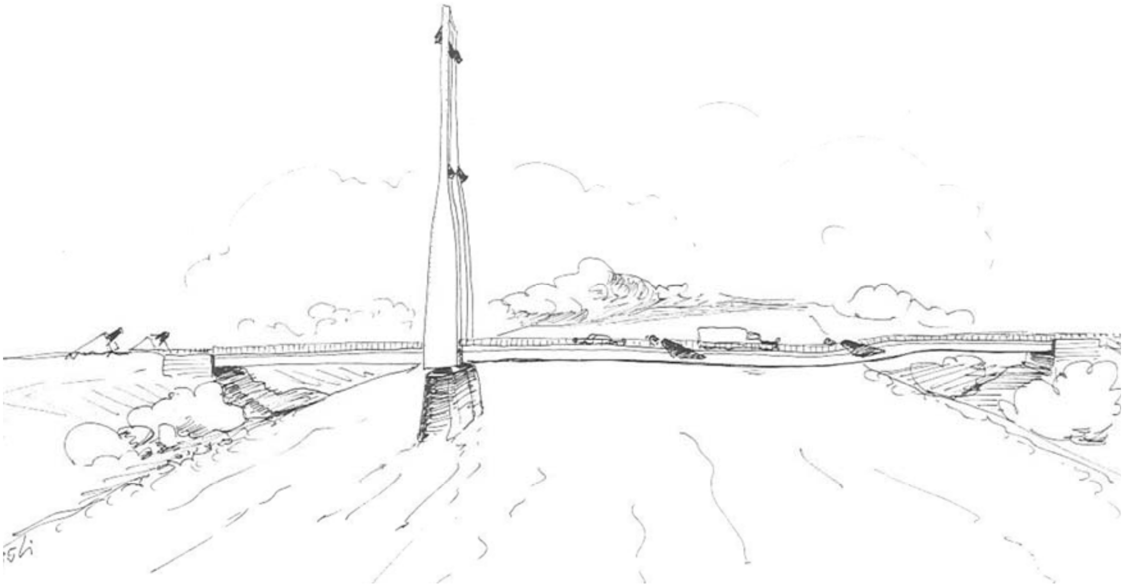

Figure 17. Cartoon to „Less is more“ (Siglat, 2010)

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